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MEASUREMENT OF THE MASS FLOW OF CROPS THROUGH A FORAGE HARVESTER

University — Université

UNIVERSITY OF ALBERTA

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

M Sc

Year this degree conferred — Année d'obtention de ce grade	Name of Supervisor — Nom du directeur de thèse
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Measurement of the Mass Flow of Crops through a Forage Harvester

by

© William Harold Mains

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Department of Agricultural Engineering

EDMONTON, ALBERTA

Spring, 1983

THE UNIVERSITY OF ALBERTA

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ABSTRACT

The objective of this study was to measure the mass flow rate of crops through a forage harvester by measuring the displacement of the upper feedroll. Two identical experiments, in which corn and alfalfa were harvested, were carried out. The experiments were a split plot design with moisture levels as the main plot. Harvest speeds and replicates were randomized within each moisture level.

The displacement of the feedroll is an indicator of mass flow rate of crops through a forage harvester, but the moisture content is a very important factor. The feedroll displacement is basically an indicator of the volume of crop harvested and moisture content determines the density. There appears to be a slight volume reduction as well as weight loss as the crops dry.

In general, feedroll displacement increased with increasing harvest rate and moisture content.

ACKNOWLEDGEMENTS

I wish to acknowledge the assistance of several people and organizations who contributed to the preparation of this thesis. My supervisor, Dr. H. P. Harrison, provided helpful suggestions and critical review.

The assistance of scientific colleagues and support staff at the Agriculture Canada Research Station, Lethbridge, Alberta was invaluable. The support given by Dr. R. Hironaka is greatly appreciated. He voluntarily spent many hours critically reviewing drafts of this thesis and his many suggestions were helpful. Mr. G. B. Schaalje assisted with the statistical analysis and interpretation of the data. Dr. G. A. Grigat provided advice on the use of the university computing system. Ms. L. J. L. Sears, the station editor reviewed the thesis. Miss M. L. Perdue and the late Mr. J. R. Williamson assisted with the field work. The figures and photographs were prepared by N. Nakahama, J. Kolpak and K. G. Sinclair.

Mr. A. Blecha expedited the return of the thesis drafts from the university computing system to my office at the Lethbridge Research Station. Mrs. C. D. Baker spent many hours with a planimeter transforming information from the recorder charts into numerical data.

My employer, Agriculture Canada, provided leave of absence and assistance so that I could complete the required courses and provided facilities and equipment at the Lethbridge Research Station for the experimental work. The

province of Alberta, through the Farming for the Future program, also provided equipment and funding.

Finally, I wish to express special gratitude to my wife, Cheryl, for her support and encouragement.

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1. INTRODUCTION

The application of additives to forage crops to improve storage conditions is common. Various granular, powder, liquid and gaseous materials are used as additives. Organic acids are used to reduce the pH of the silage; feedstuffs (grain, molasses and non-protein nitrogen) to enhance the nutrient content of the forage; fermentation aids (enzymes and bacterial cultures) to enhance the ensiling process; and a wide range of commercially available compounds to reduce storage loss and spoilage. The ratio of the applied additive to the harvested crop is usually quite small, ranging from 0.05 to 3 percent by weight.

It is difficult to obtain uniform application of an additive within the harvested crop. Spreading an additive by hand or with a fertilizer spreader in horizontal silos, with an applicator mounted on the forage harvester, or with a sprayer onto a swath are established methods of application. Uneven application occurs when applying the additive manually and an applicator which has been calibrated to the average hourly harvest rate does not allow for variation in crop; thus, at times the additive is over-applied and at other times under-applied.

Non-uniform application of some additives may have serious consequences. Low application results in poor efficacy of the additive and is costly for the results that are achieved. Over-application or non-uniform application can result in high concentrations of the additive. Urea, for

example, may be toxic to animals and can result in serious injury or death if ingested in sufficient quantities. These problems could be resolved if the application rate were more closely controlled and directly related to the throughput of the crop in the forage harvester.

The use of microprocessors, small digital computers to control machinery and processes, is widespread, (e.g., machine tools, chemical processes and other industrial applications). Microprocessor control is generally more accurate and the degree of control is superior to manual and analog controls. The application of additives to forage as it is harvested could be controlled by using a microprocessor to adjust the amount of additive applied, based on the harvest rate. The harvest rate, the amount of crop harvested per unit time, can be determined by several methods. The most direct method is to weigh the forage as it is harvested by equipping the collection vehicle with load cells. An alternate method may be to measure the displacement of the feedrolls on the harvester.

The spring-loaded feedrolls turn at a constant velocity, propelling the forage through the throat of the forage harvester into the cutting knives. The throat opening is a fixed width but the depth varies with the amount of forage passing beneath the feedrolls; thus, the instantaneous volume of forage passing into the forage harvester could be measured and, if corrected for forage density, it would indicate the weight of the forage

harvested. A microprocesser could then be programmed to sense volume changes, correct for forage density and apply the forage additive at the desired rate.

The objectives of this study are to determine if the displacement of the upper feedroll is an accurate indicator of the material flow rate through a forage harvester; to investigate the effect of crop moisture content and harvest speed on the relationship between feedroll displacement and material flow rate; and to assess the characteristics of the feedroll movement.

2. LITERATURE REVIEW

2.1 FORAGE CROP PRESERVATIVES

The value of preservatives added to forages at harvest to retain or enhance nutrient value and reduce nutrient losses of the stored crops is well established (Klinner and Shepperson 1975; Huber and Soejono 1976; Yu Yu and Thomas 1975; Henderson *et al*. 1972). Sulphur dioxide gas hastened the desired level of acidity in timothy-red clover silage (Skaggs and Knodt 1952). They also reported that the ammonia nitrogen levels, volatile acid levels and the carotene degradation were lower in the sulphur dioxide-treated silage than in the control. Sulphur dioxide added to direct cut legume silage resulted in lower pH, moisture content and fibre content but the protein level was higher than in the control (Dufour *et al*. 1954); however, there was no difference between the silages on the basis of milk production or body weight when fed to dairy cows. Carotene content was similar in the treated and untreated silages. Cowan *et al*. (1953) found that anhydrous sodium bisulfite added at the rate of 4 kilograms per tonne of unwilted forage produced silage that was superior to untreated or molasses-treated silage with respect to colour, odor and palatability. They also reported that in a wide-scale test with a large number of farmer cooperators all silages treated with sodium bisulfite were free of putrefaction and

butyric acid and were highly palatable to cattle.

Murdoch *et al.* (1955) reported that there were generally lower seepage and dry matter losses for alfalfa silages treated with formic or glycollic acids than for alfalfa silage to which molasses had been added. They reported that the acidification of the silage mass was only partially due to the added formic or glycollic acids since lactic and acetic acids, the products of fermentation, were also found. Huber and Soejono (1976) added propionic, formic and acetic acids to corn silage. The addition of propionic acid at 1.2 to 1.7% to corn silage that had a high dry matter content resulted in a cooler fermentation with greater resistance to fungal growth and spoilage than the untreated silage. Formic acid seemed more effective in preventing nutritional degradation of high moisture silage; however, the effectiveness of propionic, formic and acetic acids, when measured as an animal response (milk yield), was no different than untreated medium moisture content corn silage. Yu Yu and Thomas (1975) compared the effects of propionic acid, applied at 0.4 and 0.8%; ammonium isobutyrate, at 0.5 and 1%; and a mixture of ammonium isobutyrate and formaldehyde at 0.5% as agents to preserve alfalfa haylage harvested at 50 to 69% dry matter. All treatments reduced the temperature within the silage mass during storage but none prevented a temperature rise of the silage at the surface during the feed out period.

Essig (1968) used limestone to improve fermentation when ensiling corn. The addition of limestone enhanced the formation of the organic acids necessary for good silage, notably lactic acid. The recommended amount of limestone added to the corn should be limited to about 1% to ensure that the pH of the silage remains at 4.5 or less. Although the limestone was effective as a fermentation aid it had little effect on the average daily gain of cattle fed treated silage compared with those fed untreated control silage.

2.2 NUTRIENT ADDITIVES

Materials that increase the overall nutrient levels are often added to forage crops at harvest. Crop residues (e.g., straw and corn stover with added nutrients) are commonly used to replace forage crops in animal diets. The nutrient additives that are used vary in physical and chemical characteristics. Cereal grains have been added to grass and legume silages to increase the carbohydrate available for fermentation (Axelsson 1952; Martin *et al.* 1952) with the additional benefit of increasing the nutritional content of the silage.

Non-protein nitrogen (NPN) is commonly added to whole plant corn silage to increase the protein content. The most common NPN sources are urea (Beattie *et al.* 1971) and, more recently, anhydrous ammonia (Huber and Soejono 1976;

Buchanan-Smith 1980). These two compounds also act as forage preservatives (Ghate and Bilanski 1979; Knapp *et al.* 1975; Wilkinson *et al.* 1978; Ghate *et al.* 1981). Cattle fed corn silage treated with urea and Pro-Sil *TM*, a commercially available suspension of anhydrous ammonia in molasses and water, had an average daily gain comparable to cattle fed a diet consisting of corn silage and soybean oil meal (Beattie *et al.* 1971). The cost of feeding the animals was less when the NPN protein materials were used than when soybean oil meal was used as the protein supplement (Henderson *et al.* 1971). As well as reducing the cost, the NPN protein supplement, when added to the crop at harvest, eliminated the need for mixing when feeding.

The use of NPN sources as forage preservatives is an effective method of preventing undesirable fermentation when storing moist forages. Ghate *et al.* (1981) reported that moist hay treated with urea developed less browning, an indication of heat damage, than non-treated hay for up to six weeks after harvest. Similarly, Wilkinson *et al.* (1978) found that anhydrous ammonia was an effective method of preserving large round bales that were about 70% dry matter (30% moisture content) when harvested. They noted that the moisture content of the bales was about twice the moisture level recommended for safe storage if untreated.

The use of NPN and other chemicals to treat crop residues to produce a palatable feed for ruminant animals is of current interest. Kernan *et al.* (1977) reviewed several

techniques of producing a digestible feed from straw, including the use of sodium hydroxide. This chemical treatment of straw has been in use in Norway since the beginning of the twentieth century and is known as the Beckman procedure. They reported that urea and ammonium carbonate or bicarbonate were used in a pelleting process. They subsequently reported a simple system for treatment of straw bales with anhydrous ammonia that could easily and safely be used by farmers. Horn *et al.* (1979) treated large round bales of wheat straw with ammonia using the "cold-flo" *TM* ammonia applicator manufactured by United States Steel Corporation, Agri-chemicals Division. They found that the addition of ammonia with extra water increased the apparent protein content of the straw and the *in vitro* dry matter digestibility. There was a high loss of the applied ammonia due to the low moisture content of the straw but the loss was reduced by the addition of water to the bales.

2.3 PROPERTIES OF FORAGE AND SILAGE ADDITIVES

Many forage and silage additives have undesirable properties. The organic acids, acetic, formic and propionic, corrode harvesting equipment. Charlick (1972) reported that the average corrosion of mild steel over a seven-day period when immersed in standard commercial grade propionic acid was a reduction in thickness of 0.0017 mm/day. Further testing to determine the effectiveness of paint to resist

corrosion by propionic acid showed that there was no observable weight loss during the duration of the test for either the painted steel or the unpainted control sample; however, the acid lifted the paint film from the steel. Klinner (1975) reported difficulty in finding commercially available acid-resistant pumps with the capacity required to apply the needed amount of acid to swaths of high moisture hay.

NPN sources must be handled with care to prevent injury to humans and animals. Anhydrous ammonia can cause severe burns on exposed skin and in small quantities is an irritant to the eyes. Urea is toxic to animals if ingested in sufficient quantities. Repp *et al.* (1955) reported that lambs force fed more than 40 grams of urea died. It is important then to ensure that urea is adequately metered into the forage and that it is uniformly distributed throughout the forage mass. Reports of urea poisoning have been reported in the press. In one case where a number of animals died from urea poisoning, the concentration of urea in the silage fed to the affected animals ranged from 0.1 to 2.4% (Anon. 1979).The recommended maximum level of urea addition is 0.5%.

2.4 APPLICATION METHODS

Many methods of applying additives to forage crops have been used: fertilizer spreaders to apply granular materials, pressure reduction devices to apply high pressure gases, and modified field sprayers to apply liquids.

Bowden (1971) recommended the careful use of a spinner type fertilizer spreader to apply a thin, even layer of urea on fresh forage that had been placed in a horizontal silo. He cautioned that the urea should be carefully metered and the forage weighed to prevent possible urea toxicity. He suggested that metering the urea into the forage at the forage harvester was a better application method; however, he did not suggest how this could be accomplished when the forage harvesting rate was continually changing. Cowan *et al.* (1953) reported that many types of applicators, including mechanically driven and gravity type fertilizer spreaders, had been successfully used to apply powdered sodium bisulfite at the rate of 8 lb/ton (4 kg/tonne); however, there was no report of how uniformly the sodium bisulfite was distributed throughout the forage.

Huber and Santana (1972) and Henderson *et al.* (1971) applied the ammonia in a water-based mixture. The mixing device, described by Hansen *et al.* (1972), consisted of a perforated pipe inserted into a larger diameter solid pipe. The ammonia, supplied under pressure to the perforated pipe, was mixed with the water flowing through the larger pipe. This device was used because of high losses incurred when

adding gaseous ammonia directly to the freshly harvested forage. The development of the "cold-flo" *TM* ammonia applicator provided an improved method of adding ammonia to silage (Buchanan-Smith 1980) than the aqueous ammonia method used by Huber and Santana (1972).

Ghate *et al.* (1981) applied urea in a 1:1 mix with water and sprayed it onto a swathed crop with a truck-mounted sprayer before baling. They described a rather cumbersome and time consuming method of controlling the application of the urea spray which was applied at an average of 6.5% on a dry matter basis. A large round bale was formed with the baler, then weighed. Urea was then applied to a length of an adjacent swath equal to the length of the swath required to form the bale. The time for the sprayer to discharge the required amount of urea to the swath was calculated and the truck was then driven so that the required amount of urea solution was applied in three passes over the swath. The sprayer nozzles were adjusted so that the solution was uniformly distributed over the surface of the swath. Some mixing of the urea throughout the forage probably occurred during the baling operation.

Klinner and Holden (1978) sought to increase the uniformity of distribution of chemical preservatives by improving dispersion within the hay mass. After testing various nozzle types they found that the maximum penetration of chemical preservatives into the swath was less than 150 mm. Penetration was not increased by using air nozzles but

was improved by spraying the chemical onto the swath as it was simultaneously thinned out by momentarily accelerating it past the spray nozzles. This was accomplished by mounting the spray nozzles in a hay tedder. Klinner (1975) reported that, by visual observation, a dyed liquid sprayed onto a swath in this fashion was uniformly distributed throughout the swath.

Charlick (1972) reported that the measurement of the swath height was under study as preliminary work to the development of improved methods of matching the flow rate of the chemical additives to the throughput of hay in a baler. He found that there was a relationship between swath height and baler throughput.

Commercially available equipment has been used to apply additives to forage crops. Many authors have reported the effects of additives that have been applied with this equipment, although few authors have reported detailed additive application methods. Ghate *et al.* (1981) reported a cumbersome method of calibrating an applicator, but their method did not allow for variation within the harvested crop.

2.5 ELECTRONIC MEASUREMENT AND CONTROL

There has been limited use of electronic methods to measure the flow rates of agricultural materials. Daum and Puckett (1966) developed an electronic meter that measured

the mass flow rate of silage that was discharged from a silo by a top-unloading silo unloader. They found that there was a good correlation between the silage discharge rate and the electrical current required to operate the blower on the silo unloader. They developed electronic circuitry that automatically lowered the silo unloader so that a constant discharge rate was maintained by using a current sensing device to control the winch on the silo unloader. Hooper and Ambler (1979) developed an integrating flow meter that weighed small grains at flow rates up to 100 t/hr. The flow meter, a design based on the deflection of an impact cone, was accurate to within 5% when installed on a moving combine to weigh freshly harvested grain having moisture contents up to 18%. In a fixed location the grain flow meter was thought to be more accurate than on mobile equipment. Charlick (1972) suggested that swath height could be used as the basis for a control system to monitor crop throughput in a hay baler and adjust the flow rate of additives accordingly.

The use of feedback control systems, that is to say, systems in which information obtained from a sensor is used to adjust or control the system, is well established. Dorf (1974) noted that a float regulator used to maintain a constant level of oil in a lamp was devised in 250 BC. He also reported that in the first century AD, Heron published a book entitled "Pnuematica" that outlined several methods of regulating water level in tanks using float mechanisms. During the industrial revolution of the eighteenth century,

a number of mechanical closed loop feedback devices including Watt's flyball governor were invented (Mayer 1970). With the development of analog electronic devices, the sensitivity and response time of control systems were improved (Dorf 1974).

Microprocessors (small digital computers) have been used to control more complex systems. Wafler and Warnock (1982) used a programmable microprocessor control system that determined wet and dry bulb temperatures in the drying air of a crossflow grain dryer, calculated the relative humidity from this information and adjusted a valve on a steam line to maintain the relative humidity at a desired level.

Wilkins and Lenker (1981) compared the performance of a microprocessor-controlled planter with a conventional mechanical vegetable planter. The microprocessor-controlled planter consisted of a device that singulated the seed, a displacement sensor for the seeder unit, a thumbwheel switch to set the desired seed spacing and a microprocessor. In laboratory testing, this planter placed the seed more accurately than the mechanical planter, i.e., more uniform seed spacing, fewer skips and fewer multiple seed drops. Microprocessors have also been applied to automatic cylinder speed control for combines. Brizgis *et al.* (1980) developed a controller that automatically adjusted the cylinder speed as the moisture content of soybeans changed during the harvest period to reduce grain damage. The grain damage is

dependent on cylinder speed and the moisture content of the soybeans. An automatic controller that optimized the cylinder speed as a function of crop moisture reduced the threshing loss, compared with a manually adjusted combine. It appears feasible to use a microprocessor, with the harvest as the input, to control additive application to forage crops at the forage harvester.

2.6 SUMMARY

The use of preservatives, nutrient additives and other materials to aid harvest, reduce storage loss, improve crop quality and improve animal performance is well established. Many of the materials used are toxic, corrosive or easily volatilized; thus, the application rates are generally very low, often less than 1% of total crop weight.

Application of the chemical to the crop mass to ensure distribution of liquids throughout forages in the swath is possible; however, it is difficult to determine if the distribution is uniform. It is difficult to apply granular and powdered materials to forage in the swath and retain them. It is difficult to retain gases in a swath. The application of any type of additive to standing crops such as corn which is direct cut by the forage harvester is not feasible; however, this does not preclude applying desirable additives to the forage at harvest. There is a need to find improved methods of matching the application rate of the

additive to the rate at which the crop is harvested to ensure uniform application, reduce waste and toxic effects and, at times, reduce corrosion. Electronic methods to measure the flow rate of some agricultural materials have been developed. Microprocessors to optimize the performance of other types of agricultural machinery have been developed and are also used in industrial installations. Application of microprocessor technology to accurately control the application of additives to forage at the forage harvester, based on amount harvested, may be possible. This study reports a method to sense the harvest rate of alfalfa and silage corn through a forage harvester and the influence of harvest speed and crop moisture content on harvest rate. This information is required as a first step in the development of an additive application controller.

3. MATERIALS AND METHODS

3.1 LEVELS AND FACTORS

The data were obtained from two experiments with identical designs. A different crop was used in each experiment (i.e., corn and alfalfa). Both crops were harvested at three moisture levels and at four harvest speeds.

Alfalfa and corn have different physical characteristics. Alfalfa is relatively fine-stemmed and is easily compressed into a tightly knit mat. Corn, on the other hand, is coarse-stemmed with an ear attached at the midpoint on the stem and is not easily compressed into a tightly knit mat. The method of harvesting alfalfa is different than that of corn. Alfalfa is swathed and allowed to dry before harvesting, whereas corn is harvested directly from the standing crop. Barley, another crop that is often used for silage, is harvested in the same manner and, relative to corn, has physical characteristics similar to those of alfalfa; thus, it was not included in this study.

Three moisture levels representing the approximate mean and normal endpoints for moisture content of silage crops at harvest were used. Moisture content of silage crops at harvest is difficult to control as they are field dried, either by wilting in the swath or by natural dry down of the standing crop; thus, the crops were harvested in three

moisture classes, high, medium and low. The corn was harvested at one-week intervals as the crop matured; however, the crop dried faster between September 15 and 22 than between September 8 and 15. The alfalfa was swathed and allowed to field dry until it reached the desired moisture content. The approximate time required to dry the alfalfa was determined from preliminary trials carried out in 1981.

The corn and alfalfa were grown in separate plots to minimize the risk of damage to the alfalfa from herbicides used on the corn. The corn was grown in a continuous plot and harvested in blocks by moisture content because there was insufficient clearance for the harvesting equipment to permit growing the corn in replicates with moisture contents randomized within each replicate. The alfalfa was harvested in the same manner as the corn so that the same statistical design was used for both crops.

The rate at which the crops were harvested was determined by the speed selections available on the tractors used for harvesting. The speeds were selected to minimize loss of power take off speed to the forage harvester when operating. As a result, the harvest rate (amount of crop harvested per unit time) decreased as the moisture content of the crop decreased for a given harvest speed. The adjusted harvest rate (amount of dry matter harvested per unit time) was not affected by moisture content *per se* and reflected only the speed at which the harvesting equipment was operated.

The theoretical length of cut (TLC) for the corn and alfalfa was 9 mm. Although changing the TLC would probably affect the feedroll displacement, neither tractor had sufficient power to use a shorter TLC while maintaining the selected harvest speeds. A longer TLC is not generally reccommended because of the higher losses when the crop is ensiled (Brubaker *et al.* 1970).

3.2 EXPERIMENTAL DESIGN

The experimental layout was a split plot design with moisture content of the crop at harvest in the main plots and harvest speeds randomized within the subplots. There was no true replication of moisture levels in either experiment because the physical constraints of the equipment and the field required that each moisture level be harvested from a single plot. The field appeared uniform enough to justify the confounding of moisture levels with plots. Each main plot contained 20 subplots comprised of five replicates with four harvest speeds in each. Twenty and thirty subsamples were obtained for the corn and alfalfa, respectively, from each subplot for both variables, feedroll displacement and the mass of crop harvested. The feedroll displacement when integrated over a one-second interval was variable; thus, a large number of subsamples was required to obtain a representative mean.

The moisture levels at harvest were different for each crop, because the dry down rate for both crops was difficult to control precisely. The harvest speeds used in each experiment also differed slightly. A more powerful tractor that had different ground speeds was required to harvest the alfalfa than was required to harvest the corn. The factor levels used for each experiment are summarized in table 3.1.

Table 3.1 Factors, Levels, Notations

FACTOR	NOTATION	CROP	
		Corn	Alfalfa
Moisture Level (percent)	M1	67	78
	M2	63	72
	M3	52	63
Harvest Speed (km/hr)	S1	3.2	3.0
	S2	4.2	4.0
	S3	6.3	5.1
	S4	8.4	6.8

3.3 CULTURAL METHODS

3.3.1 CORN

Silage corn (variety Pride 1108) was planted on a 0.4-ha plot at 760 mm row spacing on May 15, 1981 at the Lethbridge Research Station. Recommended cultural practices for tillage, fertilization, irrigation and weed control required for southern Alberta were followed (Major et al. 1982). Plant population was estimated at 62,000 plants/ha and dry matter yield at 13 tonnes/ha.

3.3.2 ALFALFA

Alfalfa (variety Trek) was planted on a 3.4-ha field on June 1, 1981 at the Lethbridge Research Station. The seeding rate was 11 kg/ha. Recommended cultural practices (Johnston and Smoliak 1977) were followed. The estimated first cutting dry matter yield was 6.0 tonnes/ha. A 0.4-ha plot from the field was harvested for this experiment.

3.4 MOISTURE CONTENT OF THE CROPS

3.4.1 CORN

The moisture content of the corn was controlled by harvesting on three dates at one-week intervals: on September 8, 15 and 22, 1981. The mean moisture content on the three harvest dates was 67, 63, and 52% (wet basis),

respectively. The moisture content of the corn was not expected to decrease twice as fast between the second and third harvest dates than between the first and second.

3.4.2 ALFALFA

The moisture content of the alfalfa was controlled by swathing the crop and allowing it to field dry for different periods before harvest. The high moisture alfalfa was swathed at 0800 hours on June 17, 1982 and harvested between 1300 and 1600 hours the same day. The mean moisture content was 78%. The medium moisture alfalfa was swathed at 1400 hours on June 17th and harvested between 1300 and 1600 hours on June 18th. The mean moisture content was 72%. The low moisture content alfalfa silage was swathed at 1300 hours on June 19th. It was allowed to dry for two days before harvesting between 1300 and 1600 hours on June 21st. The mean moisture content of the low moisture content alfalfa silage was 63%.

3.5 HARVESTING EQUIPMENT

A John Deere model 3960 forage harvester fitted with a two-row rowcrop attachment was used to harvest the corn. The same harvester was fitted with a 1.5-m pickup attachment to harvest the swathed alfalfa that had been cut with a 3.5-m swather equipped with a crimper. A J. I. Case model 970 tractor (70 kW) was used as the power source when harvesting

the corn. For the alfalfa a J. I. Case model 2090 tractor (80 kW) was used. The chopped crop was collected in a 1.1 x 1.1 x 1.8 m collection box suspended from a 900-kg capacity load cell. The load cell was attached to a supporting frame fixed to a trailer towed behind the forage harvester. Rubber straps were fitted to the upper and lower corners of the collection box and attached to the supporting frame to limit movement of the box in the horizontal plane. An enclosed trailer containing the electronic recording equipment was towed behind the trailer that supported the collection box (plate 3.1).

Plate 3.1 Harvesting corn

Plate 3.2 LVDT mounted on the forage harvester

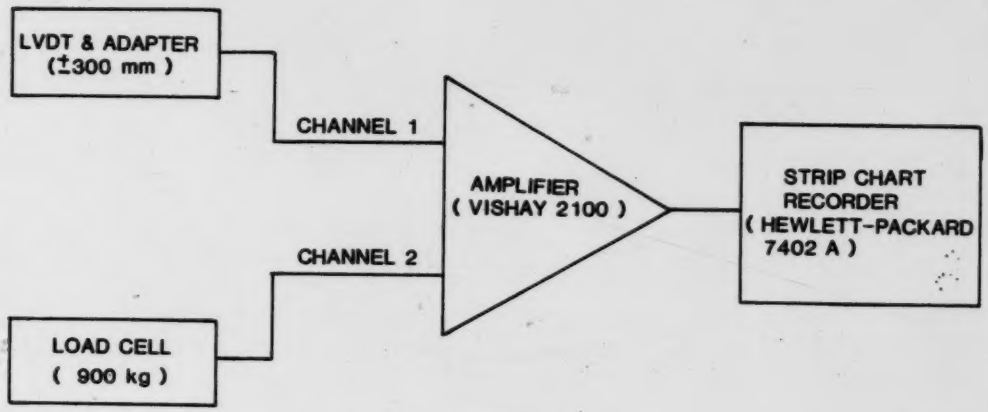

Figure 3.1 Instrumentation Block Diagram

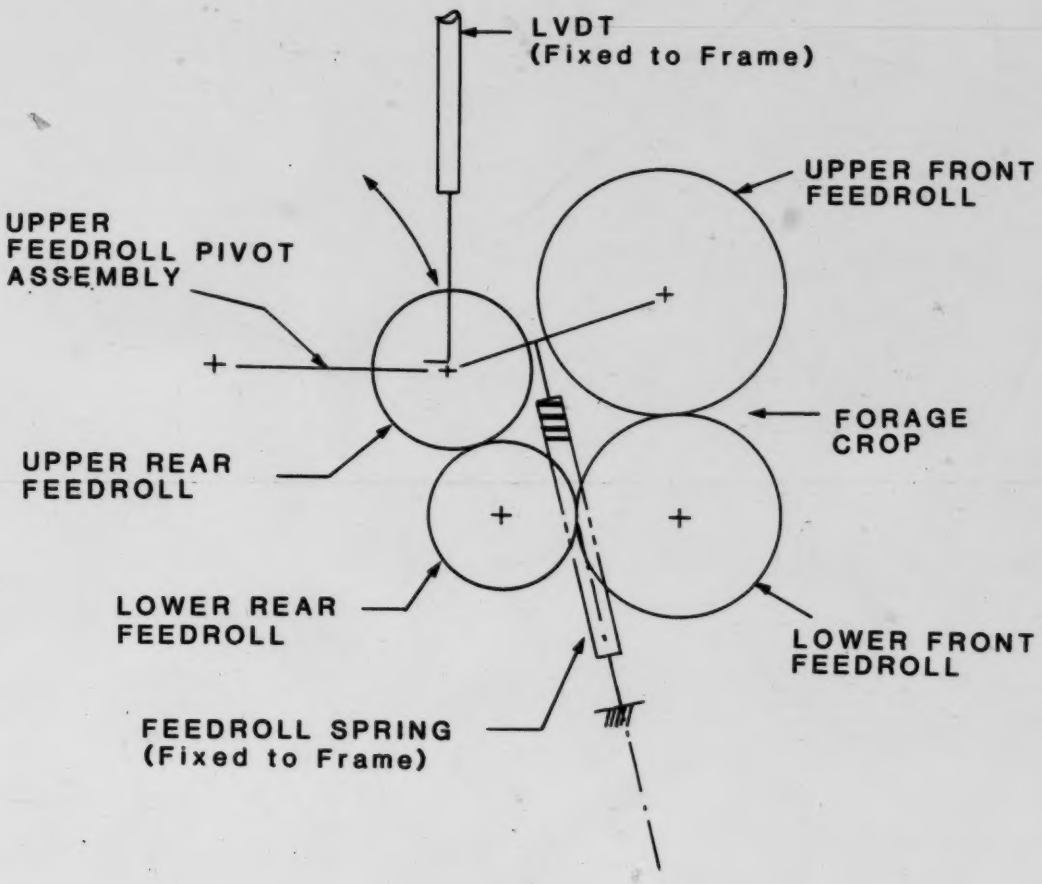

Figure 3.2 Feedroll Assembly (schematic)

3.6 HARVEST SPEEDS

3.6.1 CORN

The corn was harvested at four single-row equivalent harvest speeds. The speeds were obtained by harvesting with either one or both rows of the two-row rowcrop header on the forage harvester in combination with the two slowest gear selections on the tractor. This was effectively the equivalent of harvesting single rows of the crop at four speeds. The ground speeds were determined by measuring the time required for the tractor to travel 100 m in each of the gear selections used. The single-row equivalent speeds used were 3.2, 4.2, 6.3 and 8.4 km/hr.

3.6.2 ALFALFA

The swathed alfalfa was harvested at 4 speeds: 3.0, 4.0, 5.1, 6.8 km/hr. The tractors used had sufficient power to harvest the crops at the speeds selected; however, there was an occasional reduction of engine speed (up to 10%) at the faster harvest speeds. This caused a similar reduction in ground speed and power take off speed to the forage harvester.

3.7 INSTRUMENTATION

Both the corn and the alfalfa were continuously weighed during harvesting using a 900-kg load cell (Transducers Inc. model BTC-FF63-CS-2K). A Vishay Instruments signal conditioner (model 2100) was used to power the load cell and to amplify the signal it generated. The amplified signal was recorded on a strip chart recorder (Hewlett Packard model 7402A;figure 3.1). A 1000-microfarad capacitor was connected across the input of the recorder to dampen fluctuations of the signal that were caused by excessive movement of the collection box. The load cell was calibrated daily to give 900 kg full scale deflection on the recorder.

The displacement of the upper feedroll was measured using a 300-mm linear variable displacement transducer (LVDT) that was fitted on the forage harvester to measure only the vertical component of the feedroll displacement (plate 3.2). The feedroll was fastened to the forage harvester on an arm assembly; thus, it moved in an arc (figure 3.2). A DC-DC type LVDT (SE Labs model 373) was used to measure the feedroll displacement when the corn was harvested. The LVDT was coupled directly to the Hewlett Packard recorder. An AC-AC type LVDT (SE Labs model 361) with a Vishay model 1601 LVDT adapter, which had better amplification characteristics than the DC-DC type LVDT, was used to measure the feedroll displacement when the alfalfa was harvested. The signal from the model 361 LVDT was amplified with the Vishay signal conditioner to give 50-mm

full scale deflection on the Hewlett Packard recorder.

3.8 MOISTURE DETERMINATION

Representative samples of the chopped corn and alfalfa were obtained from each subplot. A 200-gram subsample was weighed, placed in a drying oven at 65°C for 72 hours and reweighed when dry to determine dry matter content (Baxter and Hahn 1982).

3.9 DATA REDUCTION AND HANDLING

The feedroll displacement recordings were reduced to digital form by using a planimeter to graphically determine the average displacement for one-second intervals. Thirty consecutive one-second intervals were digitized for each subplot with corn and 20 consecutive intervals on the alfalfa recordings. During the daily calibration procedure the planimeter was calibrated to the 50-mm calibration mark inscribed on the strip chart.

The strip chart recording of the weights was digitized by first inscribing a line through the middle of the weight recording. This recording appeared quite linear with respect to time except for fluctuations about the mean due to horizontal movement of the collection box during each harvest run.

The data generated for replicate 1, moisture level 1, speed 4 for corn were lost due to mechanical problems with

the recorder.

Analysis of variance of the feedroll displacement was carried out on the mean feedroll displacement (determined from 30 consecutive intervals in corn and 20 in alfalfa) to determine the effect of crop moisture content and harvest speed. Analyses of variance of harvest rate, adjusted harvest rate (i.e., dry matter harvest rate), dry matter content and dry matter yield were also carried out. Tukey's test for honestly significant differences (Steel and Torrie, 1960) was used to determine significant differences among means where appropriate.

A description of the factors and variables used in this experiment is summarized in table 3.2.

Table 3.2 Summary of measured and calculated variables and factors

FACTOR/VARIABLE	UNITS	COMMENTS
HARVEST SPEED	km/hr	calculated from time required for unloaded tractor to travel 100 meters
DRY MATTER CONTENT	percent	oven dry weight of 200-gram sample of freshly harvested crop
DISPLACEMENT	mm	continuous strip chart record of feedroll displacement with time
MASS	kg	continuous strip chart record of accumulated weight of harvested crop
HARVEST RATE	kg/min	amount of crop harvested per unit time (weight differentiated with respect to time)
ADJUSTED HARVEST RATE	kg/min	harvest rate calculated on a dry matter basis (harvest rate x dry matter content)
YIELD	kg/m	amount of crop dry matter harvested per unit length of row (corn) or swath (alfalfa) and used as an indicator of crop uniformity (adjusted harvest rate / harvest speed)

3.10 REGRESSION ANALYSIS

The data for feedroll displacement were regressed as a function of harvest rate and moisture content and as a function of adjusted harvest rate and moisture content. Standard response surface methodology and residual plot analysis, a technique to analyse the difference between the results predicted by the regression equations and the data (SAS Institute Inc. 1982), were used to determine the best fit equations. The data for adjusted harvest rate and harvest speed were analysed to determine if a relationship existed between these variables.

4. RESULTS

4.1 ANALYSIS OF VARIANCE

4.1.1 HARVEST RATE

The harvest rate for corn ranged from 116 to 408 kg/min (table 4.1) and for alfalfa from 315 to 974 kg/min (table 4.2). The harvest rate increased with increasing harvest speed and moisture content. For both corn and alfalfa, the harvest rate differed due to harvest speed ($P<.01$) and moisture content ($P<.01$)(Huth 1978). The harvest rate was influenced ($P<.05$) by the interaction of these factors (tables 4.3 and 4.4).

The adjusted harvest rate of corn was different ($P<.01$) only for harvest speeds (table 4.3). The adjusted harvest rate was not affected by moisture content or the interaction of moisture content and harvest speed. The adjusted harvest rate of corn increased with increasing harvest speed from 54 to 134 kg/min (table 4.5). The adjusted harvest rate of alfalfa differed due to harvest speed ($P<.01$) and moisture content ($P<.01$), but there was no effect on the adjusted harvest rate due to the interaction (table 4.4). The mean adjusted harvest rate of alfalfa increased with increasing harvest speed from 104 to 237 kg/min; however, at the highest moisture level, the adjusted harvest rate ranged from 90 to 211 kg/min (table 4.6).

Table 4.1 Harvest rate of corn (kg/min)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 67	63	52	Mean
3.2	165	145	116	142
4.2	209	181	143	178
6.3	321	296	207	275
8.4	408	357	292	352
Mean	276	245	190	237

Tukey's test for honestly significant differences was not applied because the interaction of harvest speed and moisture content was significant (table 4.3).

Table 4.2 Harvest rate of alfalfa (kg/min)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 78	72	63	Mean
3.0	408	386	315	370
4.0	517	508	406	477
5.1	574	664	523	587
6.8	974	887	694	852
Mean	618	612	484	572

Tukey's test for honestly significant differences was not applied because the interaction of harvest speed and moisture content was significant (table 4.4).

Table 4.3 Analysis of variance (corn)

SOURCE	D.F.	MEAN SQUARE				
		DRY MATTER CONTENT	YIELD	ADJUSTED HARVEST RATE	HARVEST RATE	DISPLACEMENT
Moisture	2	1284 ***	.0005	19	16.1 ***	1109 ***
Error A	12	17	.0106	81	.25	132
Harvest Speed	3	4	.0124	29339 ***	56.3 ***	178000 ***
Moisture x Speed	6	13	.0028	64	.74 **	250 ***
Error B	35	6	.0114	119	.22	60
Total	58					

* $P<.1$
** $P<.05$
*** $P<.01$

Table 4.4 Analysis of variance (alfalfa)

SOURCE	D.F.	MEAN SQUARE				
		DRY MATTER CONTENT	YIELD	ADJUSTED HARVEST RATE	HARVEST RATE	DISPLACEMENT
Moisture	2	1190 ***	1.83 ***	11491 ***	114005 ***	34.5 **
Error A	12	12	.17	818	11245	8.9
Harvest Speed	3	6	.02	48916 ***	641414 ***	640 ***
Moisture x Speed	6	5	.08	782	15202 **	11.3 *
Error B	36	3	.09	431	4867	5.7
Total	59					

* $P<.1$
** $P<.05$
*** $P<.01$

Table 4.5 Adjusted harvest rate of corn (kg/min)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 67	63	52	Mean
3.2	53	55	53	54
4.2	68	68	67	68
6.3	106	105	104	105
8.4	130	133	140	134
Mean *	89 a	90 a	91 a	90

* Means followed by the same letter are not significantly different ($P<.05$)

Table 4.6 Adjusted harvest rate of alfalfa (kg/min)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 78	72	63	Mean
3.0	90	110	113	104
4.0	114	144	148	136
5.1	128	184	207	173
6.8	211	242	259	237
Mean *	135 a	170 b	182 b	162

* Means followed by the same letter are not significantly different ($P<.05$)

4.1.2 DISPLACEMENT OF THE UPPER FEEDROLL

The displacement of the upper feedroll was affected ($P<.01$) by both harvest speed and moisture content in both corn and alfalfa (tables 4.3 and 4.4). The interaction of the harvest speed and moisture content was greater for alfalfa ($P<.01$) than corn ($P<.1$). In corn the feedroll displacement increased with increasing harvest speed and increasing moisture content (table 4.7; figure 4.1). At all harvest speeds, the feedroll displacement for the high moisture content alfalfa decreased from the feedroll displacement of the medium moisture content (table 4.8; figure 4.2).

The adjusted harvest rate of corn was directly proportional to the harvest speed at all moisture levels (figure 4.3). The adjusted harvest rate of the alfalfa was directly proportional to the harvest speed; however, there was a slightly different relationship at all moisture levels (figure 4.3).

Table 4.7 Feedroll displacement of corn (mm)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 67	63	52	Mean
3.2	6.0	5.4	4.9	5.5
4.2	9.3	7.1	7.7	8.0
6.3	11.6	15.4	12.0	13.0
8.4	23.1	18.0	19.2	20.1
Mean	12.5	11.5	11.0	11.6

Tukey's test for honestly significant differences was not applied because the interaction of harvest speed and moisture content was significant (table 4.3).

Table 4.8 Feedroll displacement of alfalfa (mm)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 78	72	63	Mean
3.0	5.9	5.2	3.9	5.0
4.0	9.3	9.0	7.7	8.7
5.1	10.4	15.5	12.1	12.7
6.8	20.8	22.3	17.8	20.3
Mean	11.6	13.0	10.4	11.7

Tukey's test for honestly significant differences was not applied because the interaction of harvest speed and moisture content was significant (table 4.3).

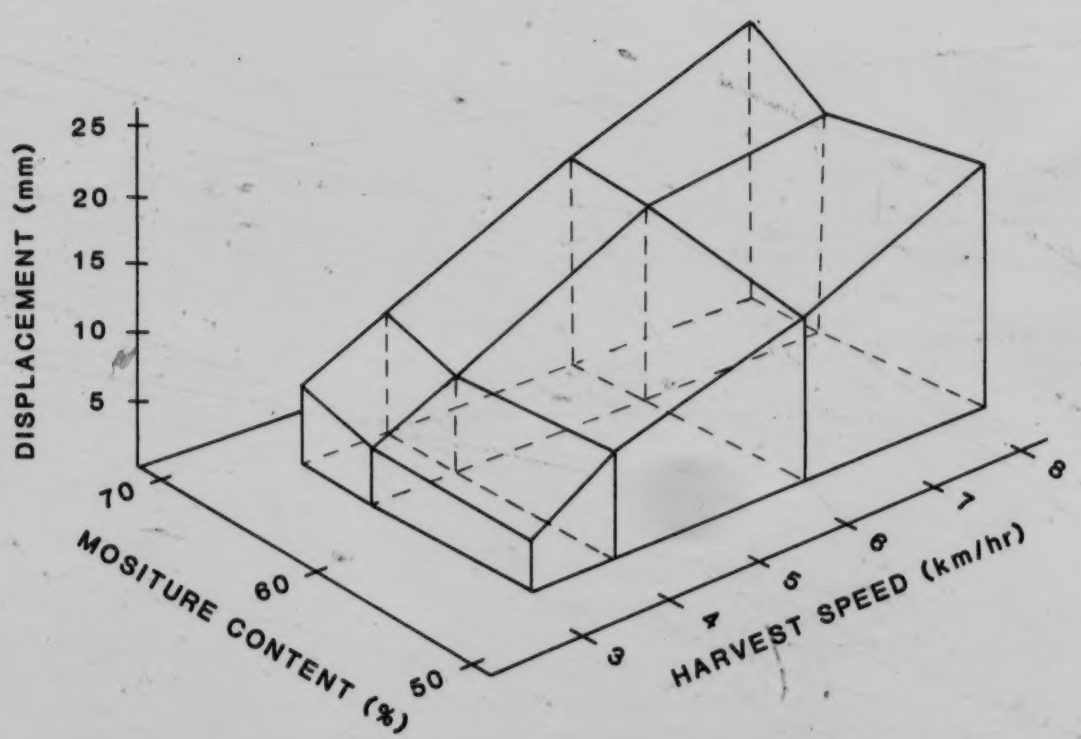

Figure 4.1 Observed feedroll displacement (corn)

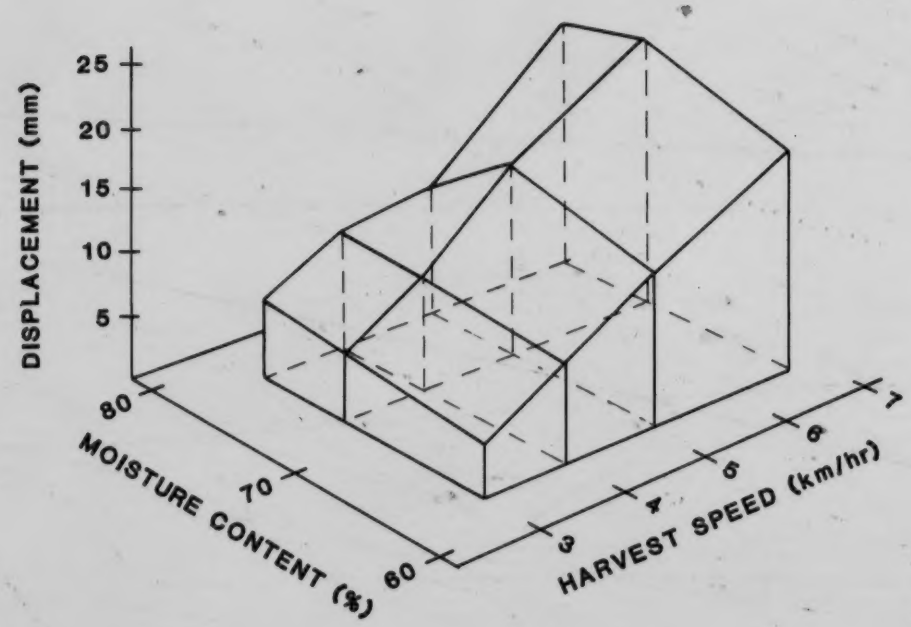

Figure 4.2 Observed feedroll displacement (alfalfa)

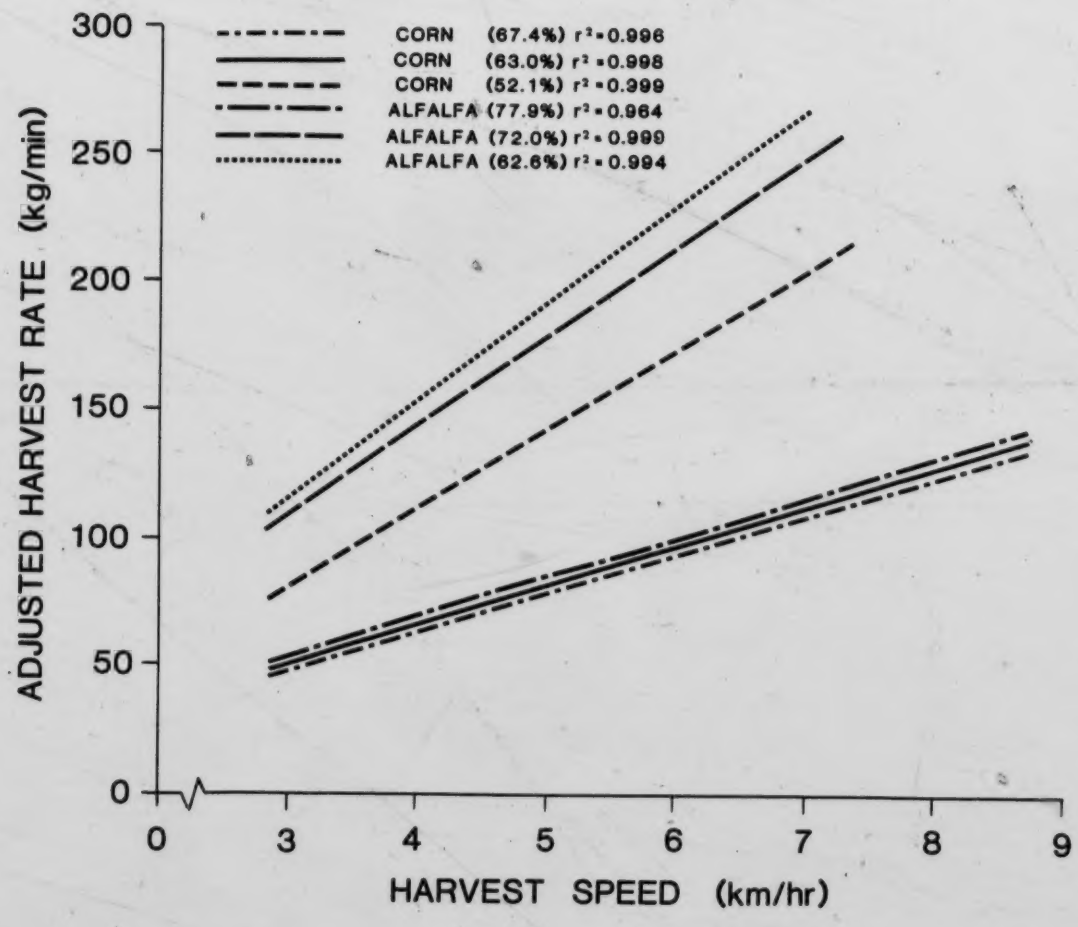

Figure 4.3 Adjusted harvest rate versus harvest speed

4.1.3 DRY MATTER CONTENT

There was a difference ($P<.01$) in the dry matter content (100 - moisture content, %) among the moisture levels at which the crops were harvested (tables 4.3 and 4.4). The mean moisture content of each moisture level was 67, 63 and 52% for corn (table 4.9) and 78, 72 and 63% for the alfalfa (table 4.10). Tukey's test for honestly significant differences (Steel and Torrie 1960) showed that the dry matter content of each crop at harvest fitted distinctly into the three moisture level classes (tables 4.7 and 4.8).

Table 4.9 Dry matter content of corn at harvest (%)

HARVEST SPEED (km/hr)	MOISTURE CONTENT CLASS		
	HIGH	MEDIUM	LOW
3.2	32	38	46
4.2	33	38	47
6.3	33	36	51
8.4	32	37	48
Mean	33	37	48
Mean moisture content *	67 a	63 b	52 c

* Means followed by the same letter are not significantly different ($P<.05$)

Table 4.10 Dry matter content of alfalfa at harvest (%)

HARVEST SPEED (km/hr)	MOISTURE CONTENT CLASS		
	HIGH	MEDIUM	LOW
3.0	22	28	36
4.0	22	28	37
5.1	22	28	40
6.8	22	27	37
Mean	22	28	37
Mean moisture content *	78 a	72 b	63 c

* Means followed by the same letter are not significantly different ($P<.05$)

4.1.4 DRY MATTER YIELD

There was no difference in the dry matter yield among the main (moisture) plots of corn (table 4.3). The average dry matter yield of the corn was 0.98 kg/m (table 4.11). The dry matter yield of alfalfa differed ($P<.01$) among the main (moisture) plots (table 4.4). The mean dry matter yield of alfalfa from plot with the highest moisture content (1.71 kg/m) was significantly lower than the yields of the other plots (table 4.12). Although the difference in dry matter yield of alfalfa between the plot with the medium moisture content (2.16 kg/m) and the plot with the lowest moisture content (2.28 kg/m) was not statistically significant, there appears to be a small difference.

Table 4.11 Dry matter yield of corn (kg/m)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 67	63	52	Mean
3.2	1.01	1.04	1.01	1.02
4.2	.97	.97	.95	.97
6.3	1.01	.99	.98	.99
8.4	.92	.94	.92	.93
Mean *	.98 a	.99 a	.97 a	.98

* Means followed by the same letter are not significantly different ($P<.05$)

Table 4.12 Dry matter yield of alfalfa (kg/m)

HARVEST SPEED (km/hr)	MOISTURE CONTENT (percent) 78	72	63	Mean
3.0	1.80	2.20	2.24	2.08
4.0	1.70	2.15	2.21	2.01
5.1	1.50	2.15	2.42	2.02
6.8	1.85	2.12	2.28	2.09
Mean *	1.71 a	2.16 b	2.28 b	2.05

* Means followed by the same letter are not significantly different ($P<.05$)

4.2 REGRESSION ANALYSIS

High coefficients of determination (r^2>>.92) were obtained for all regression equations that predict feedroll displacement as a function of harvest rate and dry matter content and as a function of adjusted harvest rate and dry matter content (table 4.13).

The regression equations describing feedroll displacement as a function of moisture content and adjusted harvest rate are plotted in figures 4.4 and 4.5 for the corn and alfalfa, respectively. For corn there was a high correlation between harvest speed and adjusted harvest rate (r^2=.99). There was a high correlation (r^2>>.96) between the harvest speed and adjusted harvest rate at each moisture level of alfalfa (figure 4.3), but the coefficient of determination was lower, r^2=.73, when the data for all moisture levels were considered together (table 4.13).

There was considerable variation of feedroll displacement with time, from 0 to 25 mm in adjacent one-second intervals (figure 4.6; appendix). It was not uncommon to record several 20 mm peaks within a one-second interval that had a mean displacement of 10 mm. The standard deviation of the mean displacement, calculated using the feedroll displacement data for all the subsamples instead of the mean feedroll displacement for each subplot, shows that the standard deviation approaches a lower limit when the displacement is calculated from 10 observations (figure 4.7).

Table 4.13 Regression Equations

CROP	REGRESSION EQUATION	r^2	STANDARD DEVIATION	
Corn	D = -11.3 + .067 x HR + .191 x DM	.93	1.63	...(1)
	HR = 187 + 13.8 x D - 2.97 x DM	.94	23.5	...(1a)
Corn	D = -6.83 + .286 x AHR - .00278 x AHR x DM + .073 x DM	.93	1.75	...(2)
	AHR = .808 + .021 x D + .0073 x D x DM - .006 x DM	.93	.190	...(2a)
Corn	AHR = .186 + 25.9 x HS	.94	.168	...(3)
Corn	HR = 63.4 + 14.4 x D	.88	31.5	...(4)
Alfalfa	D = -.234 + .011 x HR + .0007 x HR x DM - .210 x DM	.93	1.73	...(5)
	HR = 198 + 47.4 x D - .612 x D x DM + .912 x DM	.93	58.0	...(5a)
Alfalfa	D = -2.10 + .162 x AHR - .0017 x AHR x DM - .144 x DM	.93	1.67	...(6)
	AHR = .158 + 4.34 x D + .140 x D x DM + 2.22 x DM	.94	14.6	...(6a)
Alfalfa	AHR = -3.53 + 35.0 x HS	.73	30.3	...(7)
Alfalfa	HR = 212 + 30.8 x D	.88	72.8	...(8)

Legend:

D	=	Feedroll displacement	(mm)
HR	=	Harvest rate	(kg/min)
AHR	=	Adjusted harvest rate	(kg/min)
HS	=	Harvest speed	(km/hr)
DM	=	Dry matter content	(percent)

$$D = -6.83 + 0.286\ AHR - 0.0028\ AHR \times DM + 0.073 \times DM$$

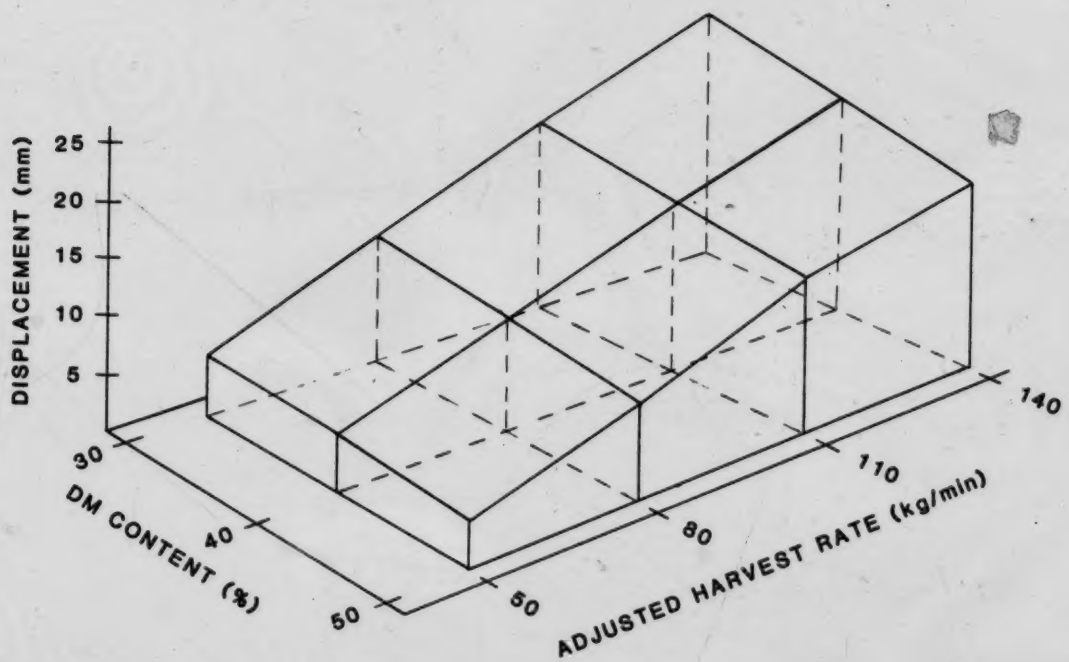

Figure 4.4 Predicted feedroll displacement (corn)

$$D = -210 + 0.162\ AHR - 0.0017\ AHR \times DM - 0.144\ DM$$

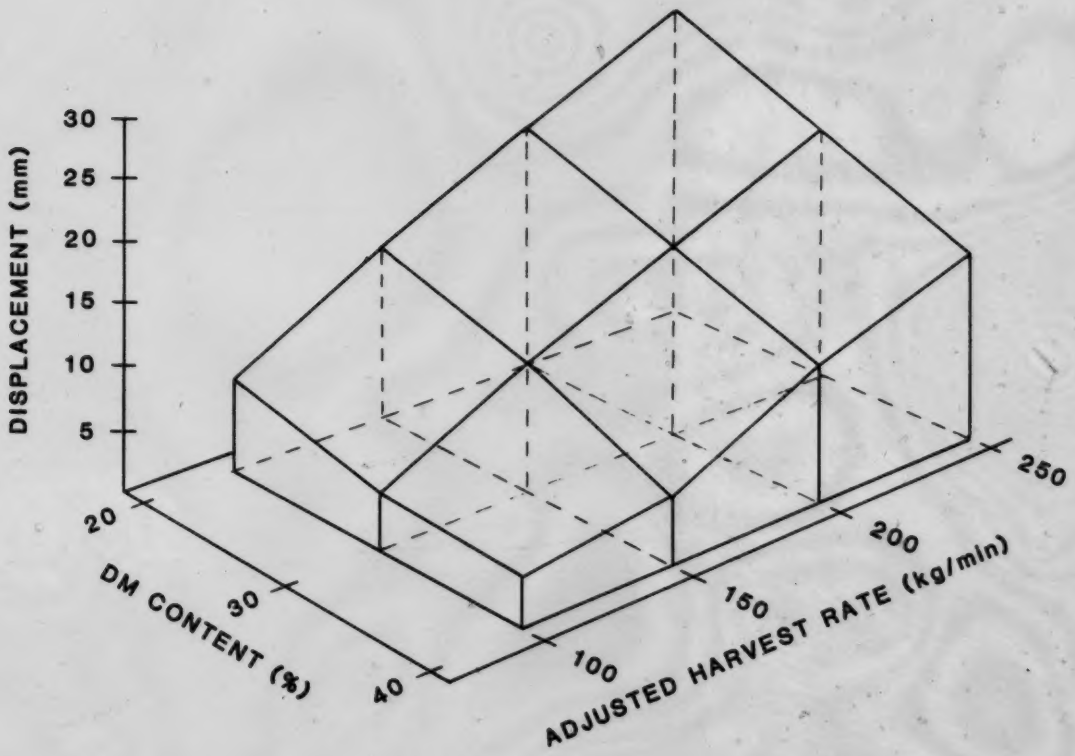

Figure 4.5 Predicted feedroll displacement (alfalfa)

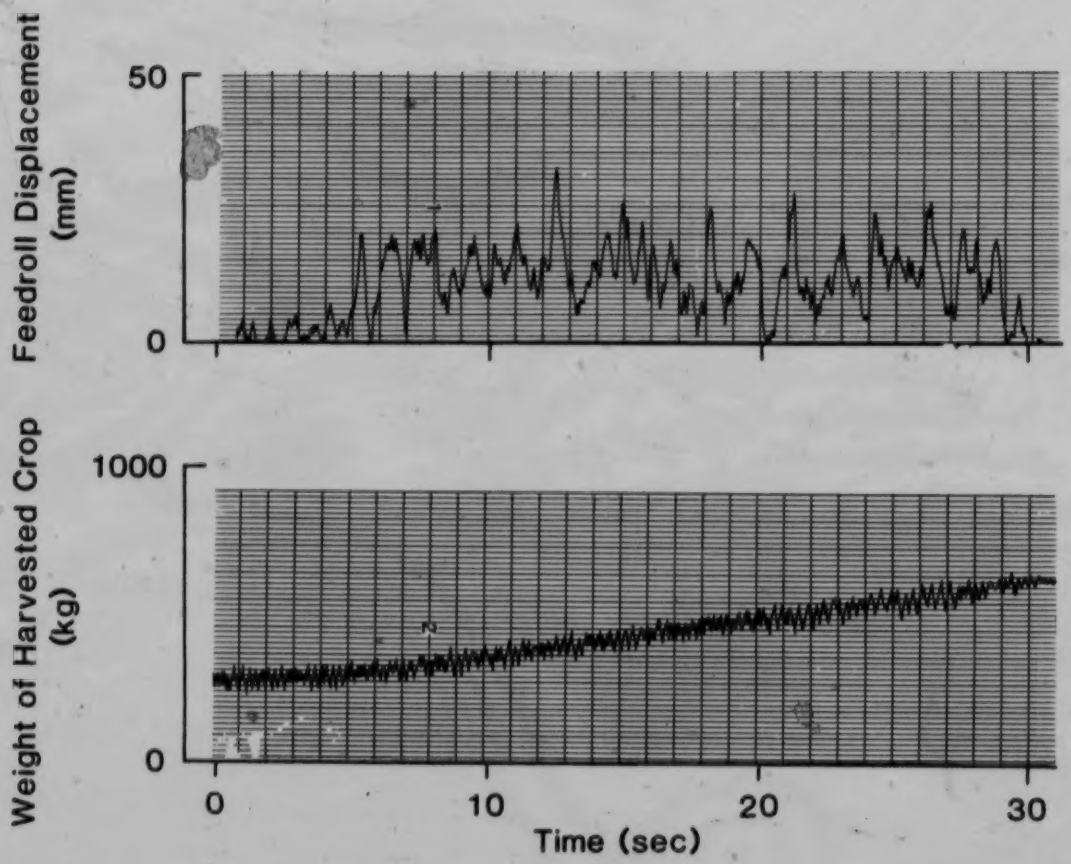

Figure 4.6 Typical strip chart recording

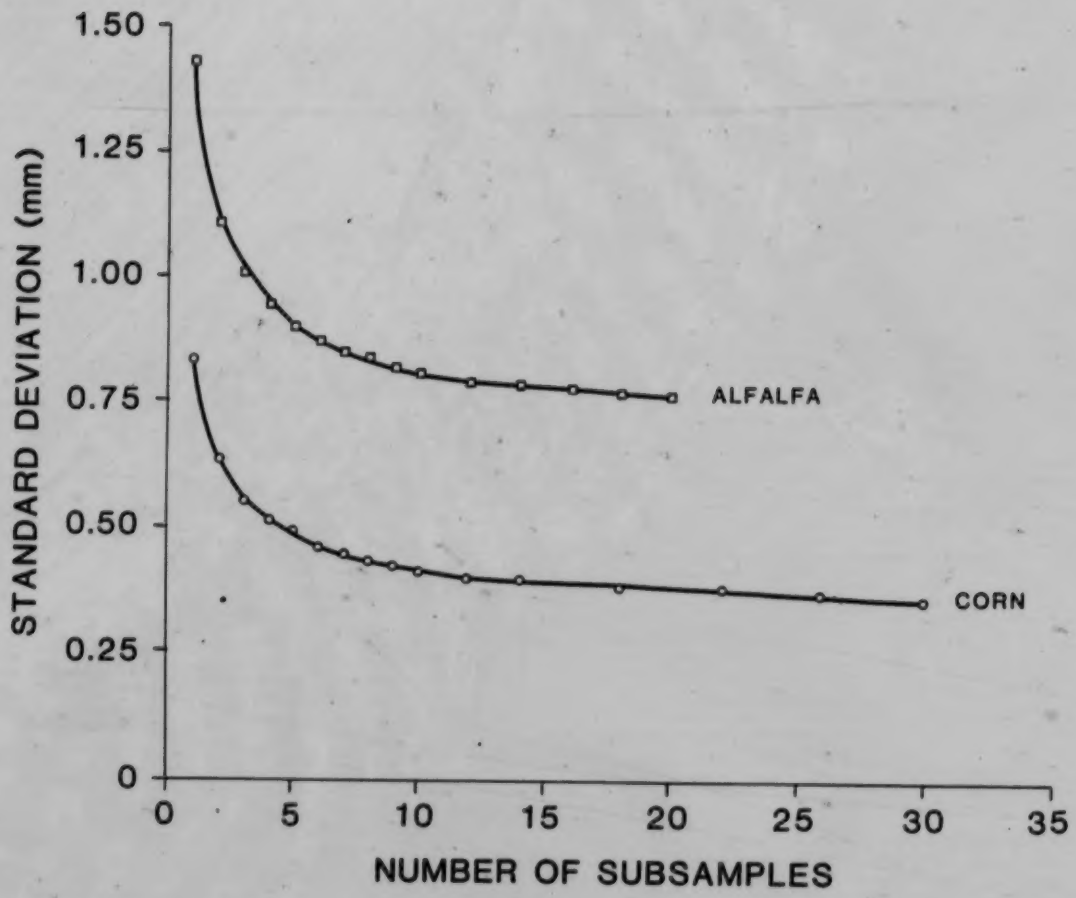

Figure 4.7 Effect of subsampling on standard deviation of feedroll displacement

5. DISCUSSION

It is possible to measure the mass flow rate of corn and alfalfa through a forage harvester by measuring the displacement of the upper feedroll. This is basically a measurement of the crop volume, and the weight of the crop is highly dependent on the moisture content. The decrease in the rate of change in the feedroll displacement (with respect to moisture content) as the moisture content of the corn decreased (figure 4.1), suggests that there was a reduction in volume, as well as weight, as the corn matured and lost moisture.

The data for the feedroll displacement for the alfalfa were more difficult to interpret than those for the corn because the alfalfa data were confounded by the lower yield in the main plot with the highest moisture content. The general decrease in feedroll displacement at the highest moisture level was not expected (table 4.8). In particular, the marked reduction in feedroll displacement with moisture 1 (78%) and harvest speed 3 (5.1 km/hr) as shown in figure 4.2 was unexpected. The low feedroll displacement is a response to the reduced yield of this plot (table 4.10).

The dry matter content term is an important part of the regression equations that were obtained to describe feedroll displacement as a function of the harvest rate or adjusted harvest rate (table 4.13). The dry matter term in the equations describing feedroll displacement as a function of harvest rate and dry matter (equations 1 and 5, table 4.13)

accounts for the weight due to the moisture within the crop. The importance of the dry matter content and the dry matter content/adjusted harvest rate terms in the regression equations describing feedroll displacement as a function of adjusted harvest rate (equations 2 and 6, table 4.13) further indicate that the volume of crop is affected by the moisture content at harvest.

It is not clear why the dry matter/harvest rate term is required in equation 4 but not in equation 1 (table 4.13). It is possible that the rate at which the crops dried affected the volume differently for alfalfa and corn. The corn dried more slowly than the alfalfa.

Because the regression equations describe feedroll displacement as a function of the harvest rate, integrating the equations with respect to time should indicate the total amount of crop harvested; however, a good correlation was not obtained between the summation of the feedroll displacements and the cumulative amount of crop harvested for each one-second interval. The poor correlation was probably caused by the short-term variation of feedroll displacement (figure 4.6). A better correlation between the summation of feedroll displacement and the cumulative amount of crop harvested could probably be obtained if the integration period was extended to include 10 one-second intervals; however, this is impractical because of the amount of forage harvested and the distance travelled by the forage harvester is too great.

The variable movement is probably due to the method used to attach the feedroll to the forage harvester. The feedroll is a large, rotating, spring-loaded assembly and, as is common in under-damped spring-mass systems, an external force acting on the system (in this case, crop displacing the feedroll) can cause initial overshoot and oscillation of the mass.

When yields were uniform, the adjusted harvest rate was directly proportional to harvest speed (figure 4.3). This reflected the effect of harvest speed on feedroll displacement. In the alfalfa the adjusted harvest rate appeared to be a function of harvest speed and moisture content (table 4.4); however, the adjusted harvest rate was affected by the lower yield of plot 1 and not the moisture content *per se* (tables 4.6 and 4.10).

The regression equations obtained for predicting feedroll displacement when harvesting corn and alfalfa cannot be directly compared using statistical methods; however, it should be noted that the regression equations for each crop have a similar mathematical form and, in equations 2 and 5 (table 4.13), vary only with respect to the constants that were obtained. A comparison of equations 2 and 5 suggests that there would be a larger feedroll deflection for corn than for alfalfa at a similar adjusted harvest rate and dry matter content.

6. SUMMARY AND CONCLUSIONS

Feedroll displacement is a good indicator of the mass flow rate of crops through a forage harvester, but methods to reduce the characteristic variability of the feedroll displacement will be required before it can be used as a sensor to control the application rate of forage additives.

When the displacement of the upper feedroll is used as the sensor, for best results accurate measurement of moisture (or dry matter) content is required to measure the mass flow rate.

The reduction in crop volumes due to moisture loss appears to be greater at the higher moisture levels than at the lower moisture levels.

The adjusted (dry matter) harvest rate was highly correlated to harvest speed when there was a uniform crop yield.

7. RECOMMENDATIONS

Further study of the nature of the feedroll movement is required before the displacement of the upper feedroll on a forage harvester can be used as a sensor for a microprocesser. The amount of feedroll damping and methods to damp either the movement of the upper feedroll or the signal from the displacement transducer are required to increase the precision of measurement of the amount of forage harvested within a shorter time period.

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9. APPENDIX

Feedroll displacement and crop weight data

The four entries (labelled A, B, C, D) required to code the data for each plot are on the following pages.

For all entries, column 1 is the data identification replicate (5); crop (1=corn, 2=alfalfa); moisture level (M1, M2, M3); harvest speed (S1, S2, S3, S4); data entry (A, B, C, D)

Data entries labelled "A" (col. 2 to 17):
crop weight and displacement data respectively for each one-second interval for time=1 to 8 seconds

Data entries labelled "B" (col. 2 to 17):
crop weight and displacement data respectively for each one-second interval for time=9 to 16 seconds

Data entries labelled "C" (corn only; col. 2 to 17):
crop weight and displacement data respectively for each one-second interval for time=17 to 24 seconds

Data entries labelled "C" (alfalfa only; col. 2 to 9):
crop weight and displacement data respectively for each one-second interval for time=17 to 24 seconds, followed by tare weight (col. 10) and dry weight of the 200-gram moisture content sample (col. 11)

Data entries labelled "D" (corn only; col. 2 to 13):
crop weight and displacement data respectively for each one-second interval for time=25 to 30 seconds, followed by tare weight (col. 14) and dry weight of the 200-gram moisture content sample (col. 15)

These data were collected at the Lethbridge Research Station while the author was an employee of the Research Branch, Agriculture Canada. The data are the property of the Government of Canada and have been made available for use by the author. The data are not available for publication in other forms without the express permission of the Director, Agriculture Canada Research Station, Lethbridge, Alberta.

1111A	167	2	172	3	176	5	176	9	181	8	181	9	185	5	185	7
1112A	331	5	335	9	340	9	340	9	344	5	349	6	349	10	353	9
1113A	167	20	172	18	181	11	185	21	190	19	195	9	199	17	204	14
1114A					MISSING		DATA									
2111A	167	8	167	7	172	8	172	10	176	3	176	6	181	7	181	7
2112A	181	7	185	7	185	8	190	9	195	7	199	9	204	10	204	9
2113A	158	10	163	12	172	10	172	18	181	13	185	14	190	14	195	14
2114A	190	29	195	25	199	23	208	20	213	16	217	20	226	21	231	25
3111A	158	7	158	3	163	5	167	3	167	8	172	4	176	9	176	1
3112A	163	15	167	10	167	5	172	5	176	9	181	10	185	10	185	7
3113A	176	13	181	11	185	19	195	17	199	10	204	25	208	14	213	11
3114A	167	18	172	20	181	15	190	24	199	22	204	20	208	25	217	19
4111A	172	7	176	4	176	9	176	5	181	6	185	9	185	9	190	1
4112A	167	8	172	6	176	6	181	10	185	9	185	7	190	10	195	6
4113A	253	19	258	18	267	20	272	18	276	22	281	19	290	19	294	21
4114A	240	22	249	26	253	29	263	23	272	29	281	21	290	28	294	28
5111A	190	3	195	1	199	3	199	5	204	6	204	2	208	4	213	3
5112A	231	6	235	9	240	5	240	7	244	6	249	10	249	8	253	6
5113A	185	16	185	13	190	15	199	15	204	17	208	19	217	19	222	18
5114A	217	18	222	17	226	16	235	20	244	18	253	22	258	21	263	22
1121A	172	7	172	3	177	8	177	2	181	5	181	2	186	1	186	5
1122A	185	6	185	8	190	4	190	9	195	6	195	5	199	9	199	5
1123A	163	17	167	17	172	19	176	15	181	11	185	10	190	12	195	9
1124A	163	17	167	18	172	12	181	14	185	18	190	15	199	13	204	18
2121A	149	2	154	5	158	2	158	5	163	4	163	5	167	5	167	5
2122A	158	7	163	5	163	5	167	3	172	10	176	8	181	5	181	10
2123A	172	12	176	14	181	9	185	7	190	12	195	10	199	13	204	12
2124A	163	16	167	18	172	22	181	22	185	12	190	10	195	18	199	12
3121A	172	4	176	1	176	7	181	5	181	9	181	4	185	3	190	3
3122A	181	9	181	6	185	5	190	5	195	5	199	5	199	5	204	7
3123A	181	17	185	16	190	10	195	15	199	11	204	13	208	16	217	11
3124A	149	10	154	15	158	10	163	7	172	10	181	5	185	15	190	18
4121A	213	3	213	5	217	5	217	8	217	7	222	11	222	2	226	9
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4123A	185	20	190	19	195	20	199	19	204	16	213	20	217	21	222	17
4124A	163	20	167	16	176	20	181	17	185	18	195	10	199	15	204	20
5121A	222	5	222	3	226	5	226	5	231	4	235	10	235	7	240	6
5122A	235	10	235	10	240	7	244	7	249	17	249	9	253	18	258	15
5123A	244	15	253	16	258	18	263	19	267	13	272	13	276	16	281	14
5124A	181	23	190	21	195	20	199	20	208	23	213	20	217	17	226	19
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1132A	163	5	167	8	167	7	167	2	172	5	176	6	176	5	181	5
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5131A	185	8	185	7	185	2	190	4	195	9	195	4	199	8	204	5
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5133A	167	14	172	14	176	6	176	16	181	15	185	9	185	10	190	10
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1111B	190	5	195	3	199	7	199	5	204	2	204	6	208	8	213	6
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1113B	208	20	217	16	222	20	226	16	231	18	235	18	240	24	244	19
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2113B	199	16	204	13	208	12	213	18	217	14	226	10	231	14	235	14
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1123B	199	14	204	13	208	10	213	17	217	13	222	11	226	10	231	9
1124B	213	15	217	20	226	18	231	15	235	19	244	21	253	20	258	17
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1132B	185	7	185	5	185	7	190	7	195	6	195	6	195	11	199	9

1133B	195	12	199	11	204	15	204	8	208	12	213	3	217	12	222	9
1134B	222	19	226	17	231	22	235	18	240	19	244	14	253	16	258	18
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4132B	167	10	172	6	176	4	176	7	181	7	181	9	185	5	185	10
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5133B	195	9	199	19	204	4	204	15	208	16	213	14	213	15	217	15
5134B	195	19	199	20	204	19	208	17	213	18	217	14	222	15	226	19
1111C	213	6	217	2	222	5	222	5	226	6	231	1	231	5	235	7
1112C	385	8	390	7	394	16	394	7	399	6	403	9	408	11	412	9
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3111C	204	8	204	4	208	8	213	9	213	4	217	5	217	8	222	3
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4111C	213	9	213	12	213	8	217	10	222	10	222	4	226	6	231	10
4112C	226	15	231	12	231	13	235	13	240	11	240	11	244	10	249	12
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4114C	362	29	371	28	380	27	390	23	399	20	408	25	417	28	421	21
5111C	240	8	244	8	249	5	253	3	253	8	258	10	258	9	263	3
5112C	285	6	290	6	294	7	294	12	299	5	303	4	308	11	312	7
5113C	272	19	276	18	285	12	290	24	294	20	299	21	308	21	312	19
5114C	321	25	326	27	335	28	344	25	349	24	353	25	362	28	367	28
1121C	199	2	204	1	204	4	208	16	208	6	213	2	213	4	217	1
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1123C	235	10	240	12	244	12	249	14	253	19	258	10	263	15	267	11
1124C	263	19	272	19	276	20	281	20	290	17	299	16	303	17	308	23
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2122C	217	10	217	5	217	9	222	7	226	10	231	10	235	8	235	3
2123C	244	15	253	13	253	17	258	16	263	16	272	16	276	12	281	19
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2132C	185	9	190	12	195	8	195	10	195	11	199	9	204	16	204	9
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1111D	240	8	240	7	244	9	249	9	249	9	253	8	163	62		
1112D	412	12	417	10	421	3	426	8	430	6	430	14	326	64		
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2114D	331	23	335	20	340	22	344	22	353	19	358	23	181	68		
3111D	222	3	226	8	226	8	231	5	231	5	235	12	158	72		
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4112D	253	14	258	10	258	13	263	12	267	11	272	10	167	65		
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4114D	430	23	435	19	444	23	453	24	458	21	467	22	235	59		
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5112D	312	9	317	10	321	9	321	9	326	7	331	7	226	65		
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1123D	272	13	276	13	281	13	285	13	290	12	294	11	158	73		
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2121D	222	9	226	7	231	5	235	7	240	5	244	10	163	75			
2122D	235	10	240	4	244	4	249	6	253	9	253	10	154	71			
2123D	285	18	290	20	294	17	299	14	303	17	308	14	167	74			
2124D	299	17	303	22	308	23	317	19	321	20	326	19	158	73			
3121D	231	3	231	2	235	6	235	8	235	2	240	7	172	76			
3122D	258	8	263	6	267	10	272	8	272	9	276	8	176	75			
3123D	299	12	303	19	308	13	312	14	317	13	326	16	176	72			
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5122D	312	7	312	8	317	6	321	10	326	8	331	9	231	78			
5123D	362	17	367	18	376	11	380	14	385	14	390	19	240	69			
5124D	326	19	335	20	340	21	344	19	353	21	358	24	176	67			
1131D	321	4	326	5	326	5	331	6	331	3	331	4	281	88			
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1133D	249	8	253	11	258	17	258	9	263	10	267	14	167	94			
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2131D	213	4	213	2	213	8	217	5	222	7	222	6	158	89			
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2134D	285	19	290	20	294	20	303	22	308	19	312	23	163	93			
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3133D	253	14	258	9	258	17	263	14	267	15	267	15	163	11			
3134D	281	22	285	20	290	21	294	20	303	21	308	23	154	96			
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5134D	267	17	272	20	276	15	276	19	281	19	285	18	154	10			
1211A	634	8	643	3	648	0	653	6	657	4	666	0	671	5	680	0	
1212A	267	5	272	10	276	12	285	11	290	11	299	11	308	11	317	10	
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2212A	226	17	244	9	253	5	272	10	281	16	294	7	308	12	321	20	
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5212A	253	7	258	8	267	9	272	7	276	9	285	14	290	15	299	13
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1223A	417	14	426	11	435	5	448	17	458	16	467	18	476	16	485	19
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3221A	471	6	476	3	480	10	489	2	494	2	503	5	507	3	512	7
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3224A	235	7	244	20	253	23	272	25	285	22	299	14	312	17	326	11
4221A	471	10	476	11	485	8	494	9	503	6	507	2	516	11	526	5
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5224A	244	23	263	28	276	38	294	28	312	32	326	31	344	26	362	23
1231A	489	2	494	6	498	1	503	2	507	6	512	1	516	4	521	3
1232A	235	6	240	0	249	6	253	9	263	5	267	7	276	7	285	1
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2232A	380	5	385	5	394	5	399	6	403	6	412	6	417	6	421	5
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2234A	444	11	453	17	462	18	480	14	489	13	503	15	512	15	526	15
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4231A	480	8	485	9	489	0	494	2	498	4	503	0	507	0	507	0
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4233A	235	6	244	30	253	15	263	20	272	8	281	16	290	12	299	9
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5233A	553	12	562	13	566	15	575	10	580	9	589	10	598	7	603	8
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1211B	680	1	689	0	693	4	698	5	702	5	707	3	711	7	721	7
1212B	326	12	331	10	340	5	344	10	353	5	362	3	367	3	376	3
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2213B	326	15	335	10	344	12	358	8	371	17	380	17	394	16	408	13
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4211B	476	13	485	9	489	11	498	7	507	6	516	5	526	2	530	12
4212B	748	13	761	11	775	13	784	13	798	13	807	14	816	17	829	20
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1223B	494	18	507	16	516	17	526	18	535	22	544	20	557	20	566	16
1224B	335	20	344	20	362	15	371	13	385	17	399	20	412	18	426	26
2221B	571	3	580	5	585	6	589	2	598	7	603	7	607	3	616	4
2222B	326	7	340	9	344	9	358	8	367	11	376	10	390	11	399	14
2223B	340	12	349	16	362	13	371	16	380	12	394	19	403	20	412	16
2224B	344	23	358	21	376	24	390	20	399	19	417	18	430	28	444	19
3221B	521	5	526	4	530	5	535	2	544	7	548	7	553	8	562	3
3222B	294	7	303	4	308	8	317	5	326	3	331	5	340	8	349	9
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3224B	344	18	349	15	371	18	385	20	399	28	412	17	430	12	439	11
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1231B	526	2	530	1	535	9	539	3	544	0	548	1	553	3	557	3
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1233B	299	11	308	18	317	17	326	20	340	32	349	17	358	17	367	14
1234B	535	18	548	21	557	24	571	23	580	20	594	25	607	21	616	19
2231B	276	1	285	2	290	3	294	3	299	2	303	7	308	5	312	3
2232B	430	5	435	7	444	5	453	10	458	3	462	1	467	6	471	9
2233B	299	10	308	15	317	10	326	6	335	7	344	10	353	9	362	7
2234B	539	13	548	23	562	20	575	29	585	18	598	19	612	21	621	16
3231B	562	3	566	4	575	5	580	1	585	6	594	2	598	0	603	2
3232B	312	7	317	12	321	19	326	14	335	6	344	1	349	0	358	12
3233B	480	17	489	25	503	23	512	8	521	0	530	0	539	26	553	18
3234B	317	14	326	12	335	25	344	25	358	15	367	11	376	23	385	20
4231B	512	5	516	3	521	5	526	9	530	7	535	0	539	1	544	7
4232B	643	13	648	9	657	10	666	6	671	4	675	13	684	6	689	7
4233B	308	20	317	16	326	18	335	27	344	11	353	9	362	15	371	9
4234B	335	23	349	20	358	28	371	25	385	20	394	27	408	28	417	24
5231B	267	3	272	4	281	9	285	7	294	10	303	5	308	3	312	8

5232B	471	13	476	9	485	7	494	14	503	11	507	11	516	9	526	8
5233B	612	10	616	7	621	5	630	7	639	9	648	9	653	7	662	12
5234B	326	23	340	15	353	18	367	16	380	23	394	24	408	16	417	14
1211C	725	4	730	7	739	5	743	8	634	42						
1212C	385	2	394	2	399	1	408	4	263	42						
1213C	634	10	643	10	653	12	662	10	494	43						
1214C	489	20	507	21	526	20	539	18	235	45						
2211C	653	10	662	7	671	11	675	9	530	40						
2212C	439	21	453	23	467	12	471	7	244	44						
2213C	417	15	430	9	439	14	453	14	226	45						
2214C	639	21	662	26	680	23	698	29	326	39						
3211C	349	5	358	4	367	3	376	5	235	44						
3212C	621	2	630	5	634	5	643	12	507	46						
3213C	430	9	439	5	448	11	458	14	253	42						
3214C	702	23	721	26	734	18	752	20	435	40						
4211C	539	17	544	6	553	2	562	7	408	49						
4212C	838	20	852	17	866	17	875	13	657	44						
4213C	371	5	380	3	390	6	399	1	235	53						
4214C	494	29	507	23	526	20	539	22	217	45						
5211C	721	6	725	8	734	6	743	4	612	45						
5212C	362	0	367	3	376	1	380	8	244	45						
5213C	616	14	621	10	634	12	643	20	448	41						
5214C	485	14	498	19	512	20	526	25	217	48						
1221C	326	2	331	3	340	5	344	4	231	55						
1222C	376	6	380	6	390	10	399	11	249	54						
1223C	575	20	585	17	598	20	607	12	403	55						
1224C	439	21	453	20	467	17	480	17	217	55						
2221C	621	4	630	2	634	4	639	3	516	55						
2222C	408	12	417	10	430	11	439	11	235	52						
2223C	421	8	435	12	448	15	458	10	240	51						
2224C	458	25	471	29	485	23	503	25	217	49						
3221C	566	5	571	6	580	5	585	4	462	56						
3222C	358	7	362	7	371	9	380	8	235	59						
3223C	535	18	544	18	557	14	571	17	353	54						
3224C	458	19	471	24	485	30	498	24	217	59						
4221C	603	9	607	7	616	8	625	12	462	69						
4222C	371	9	380	6	390	12	399	17	222	65						
4223C	394	7	399	3	412	21	421	19	231	65						
4224C	485	27	503	30	516	23	530	21	235	58						
5221C	594	6	598	6	603	11	612	4	489	47						
5222C	376	6	385	5	399	7	408	7	235	54						
5223C	693	24	707	17	721	20	734	13	458	54						
5224C	526	35	544	33	562	35	580	26	226	52						
1231C	562	0	566	0	571	1	575	3	489	75						
1232C	349	7	358	3	362	6	367	5	235	76						
1233C	376	9	385	8	394	8	403	16	217	81						
1234C	630	16	639	20	653	9	666	11	430	81						
2231C	321	14	326	2	331	3	340	6	231	71						
2232C	480	2	485	5	489	7	498	3	376	71						
2233C	367	8	376	6	385	11	394	18	226	77						
2234C	634	18	648	15	662	12	671	14	430	77						

3231C	612	8	616	1	621	2	630	6	512	74
3232C	362	7	367	2	371	11	380	5	258	72
3233C	562	0	571	22	580	11	589	0	399	76
3234C	394	7	403	5	412	11	421	39	231	76
4231C	544	3	548	4	553	2	557	0	476	71
4232C	698	8	707	11	711	13	721	10	580	71
4233C	380	6	390	24	399	0	408	7	226	80
4234C	430	30	444	26	458	27	467	22	226	70
5231C	317	6	326	6	331	6	340	8	208	67
5232C	530	10	539	11	548	12	557	5	399	75
5233C	671	15	675	11	684	6	689	5	544	83
5234C	430	18	444	19	453	17	467	21	217	70